CLAIMS

What is claimed is:

1. A method of carrier phase detection in a demodulated signal formed from a data-modulated carrier, comprising the steps of:

a) generating, from the signal, an estimate of an angle between the carrier and a locally generated reference based on a stochastic gradient of a single-axis cost function, the cost function being a Bussgang-class cost function; and

b) adjusting at least one of the frequency and phase of the demodulated signal based on the angle such that the magnitude of the angle is driven toward a predetermined value.

2. The invention as recited in claim 1, wherein step a) generates the estimate by the steps of:

a1) calculating a SA cost function error term based on the demodulated signal;

a2) forming an approximation of a derivative of the demodulated signal with respect to the angle; and

a3) combining the SA cost function error term with the approximation to form a phase error; and

a4) generating the angle from the phase error.

3 The invention as recited in claim 2 wherein, for step a), the single-axis cost function is a single-axis constant modulus criterion J_{CM}.

4. The invention as recited in claim 3, wherein, for step a3) the phase error is the stochastic gradient of the single-axis constant modulus criterion J_{CM} ($dJ_{CM}/d\theta$) given by:

$$dJ_{CM}/d\theta = 4e_{SA\text{-}CM}[n]\ DT[n],$$

where $e_{SA\text{-}CM}$ is the SA cost function error term defined by $(\mathrm{Re}\{y_n(\theta)\}^2 - \rho^2)\mathrm{Re}\{y_n(\theta)\}$, $y_n(\theta)$ is input data based on the demodulated signal, and $DT[n]$ approximates a derivative of the demodulated signal with respect to the angle θ ($d(y_n(\theta))/d\theta$).

5. The invention as recited in claim 4, wherein $e_{SA\text{-}CM}[n]$ is based on a rotated signal

$y_n(\theta)e^{-j\theta[n-1]}$, and DT[n] is equivalent to:

$$\mathrm{Re}\{y_n(\theta)e^{-j\theta[n]}\} = \mathrm{Re}\{y_n(\theta)\}\cos(\theta[n]) + \mathrm{Im}\{y_n(\theta)\}\sin(\theta[n]),$$

where Re{•} extracts the (real) I component.

6. The invention as recited in claim 4, wherein $e_{SA\text{-}CM}[n]$ is based on a rotated data signal $y_n(\theta)e^{-j\theta[n]}$ adjusted to account for feedback filter equalization, and D[n] is equivalent to:

$$\mathrm{Re}\{y_n(\theta)e^{-j\theta[n]}\} = \mathrm{Re}\{y_n(\theta)\}\cos(\theta[n]) + \mathrm{Im}\{y_n(\theta)\}\sin(\theta[n]),$$

where Re{•} extracts the (real) I component.

7. The invention as recited in claim 4, wherein $e_{SA\text{-}CM}[n]$ is based on a decision d[n] for a rotated data signal $y_n(\theta)e^{-j\theta[n]}$ adjusted to account for feedback filter equalization ($y_n(\theta)e^{-j\theta[n]}$-w[n]), the decision d[n] given as:

$$f(\mathrm{Re}\{y_n(\theta)e^{-j\theta[n]}-w[n]\})$$

where f(•) denotes the decision function which operates on a real-valued data signal, and DT[n] is equivalent to:

$$f'(\mathrm{Re}\{y_n(\theta)e^{-j\theta[n]}-w[n]\})\ \mathrm{Im}\{y_n(\theta)e^{-j\theta[n]}-w[n]\}$$

where Im{•} extracts the (imaginary) Q component, and f'(•) is the derivative of the decision function.

8. The invention as recited in claim 4, wherein $e_{SA\text{-}CM}[n]$ is based on the data signal $z[n]e^{-j\theta[n]}$, where $z[n]= y_n(\theta)-w[n]$, $y_n(\theta)$ is the data signal having forward filter equalization, and w[n] is the feedback filtered equalized data signal, and DT[n] is equivalent to:

$$\mathrm{Re}\{y_n(\theta)-w[n]\}\cos(\theta[n]) + \mathrm{Im}\{y_n(\theta)-w[n]\}\sin(\theta[n]).$$

9. The invention as recited in claim 4, wherein $e_{SA\text{-}CM}[n]$ is based on a real component of a decision d[n], Re{d[n]}, for a rotated data signal $y_n(\theta)e^{-j\theta[n]}$ adjusted to account for feedback filter equalization ($y_n(\theta)e^{-j\theta[n]}$-w[n]), the decision d[n] given as:

$$f(\mathrm{Re}\{y_n(\theta)e^{-j\theta[n]}-w[n]\})$$

where f(•) denotes the decision function which operates on a real valued data signal, and DT[n]

is equivalent to:

$$f'(\mathrm{Re}\{(y_n(\theta)-w[n])\, e^{-j\theta[n]})\}) \, \mathrm{Re}\{(y_n(\theta)-w[n])e^{-j\theta[n]}\}$$

where Re{•} extracts the (real) I component, and f'(•) is the derivative of the decision function..

10. The invention as recited in claim 3, wherein, for step b), adjusting the locally generated reference includes the step of shifting, in frequency, the demodulated signal substantially to baseband.

11. The invention as recited in claim 2, further comprising the steps of:

c) generating a signal quality measure (SQM) from the received signal; and

d) generating at least one other cost error term based on a corresponding cost criterion, and wherein

step a) generates the angle based on the SQM.

12. The invention as recited in claim 11, wherein step a) generates the angle based on the SQM by the step of adaptively switching between either i) one of the cost error terms, or ii) a weighted combination of cost error terms that is combined with the approximation of the derivative.

13. The invention as recited in claim 11, wherein one of the cost error terms is a least mean square error term.

14. The invention as recited in claim 11, wherein one of the cost error terms is a CMA error term.

15. The invention as recited in claim 1, further comprising the steps of applying equalization to the demodulated signal with forward and/or feedback filters.

16. The invention as recited in claim 15, wherein step a) generates the estimate of the angle based on the equalized, demodulated signal.

17. The invention as recited in claim 15, further comprising the step of generating a decision for the data of the equalized, demodulated signal, and wherein step a) generates the estimate of the angle based on the decision for the data of the equalized, demodulated signal.

18. The invention as recited in claim 1, wherein step a) generates the estimate of the

angle based on both the equalized, demodulated signal and on the decision for the data of the equalized, demodulated signal.

19. The invention as recited in claim 15, wherein the step of applying equalization applies either linear equalization or decision feedback equalization.

20. The invention as recited in claim 15, wherein step a) generates the angle based on a SA cost function error term that is generated during equalizer adaptation as tap-coefficients are updated by applying equalization to the demodulated signal.

21. The invention as recited in claim 15, wherein the step of applying equalization employs the feedback filter operating on signals either in the passband or substantially near the baseband derived from the forward filter.

22. The invention as recited in claim 1, wherein, for step a), the data-modulated signal is the carrier modulated by the data in accordance with a vestigial sideband (VSB) format.

23. The invention as recited in claim 1, wherein, for step a), the data-modulated signal is a digital television signal having its data encoded in accordance with an ATSC standard.

24. Apparatus for carrier phase detection in a demodulated signal formed from a data-modulated carrier, the apparatus comprising:

a carrier tracking loop configured to generate an estimate of an angle between the carrier and the locally generated reference from the signal and based on a stochastic gradient of a single-axis cost function, the cost function being selected from a set of Bussgang-class cost functions; and

a rotation combiner adapted to adjust at least one of the frequency and phase of the demodulated signal with the angle such that the magnitude of the angle is driven to a predetermined value.

25. The invention as recited in claim 24, wherein the carrier tracking loop comprises:

a1) phase detector calculating an SA cost function error term based on the demodulated signal;

a2) a first circuit configured to form an approximation of a derivative of the received

signal with respect to the angle; and

a3) a rotation combiner configured to combine the SA cost function error term with the approximation to form a phase error; and

a4) a second circuit configured to generate the angle from the phase error.

26. The invention as recited in claim 25, wherein the single-axis cost function is a single-axis constant modulus criterion J_{CM}.

27. The invention as recited in claim 26, wherein the phase error is the stochastic gradient of the single-axis constant modulus criterion J_{CM} ($dJ_{CM}/d\theta$) given by:

$$dJ_{CM}/d\theta = 4e_{SA\text{-}CM}[n]\ DT[n],$$

where $e_{SA\text{-}CM}$ is the SA cost function error term defined by $(\mathrm{Re}\{y_n(\theta)\}^2 - \rho^2)\mathrm{Re}\{y_n(\theta)\}$, $y_n(\theta)$ is input data based on the demodulated signal, and DT[n] approximates a derivative of the demodulated signal with respect to the angle θ ($d(y_n(\theta))/d\theta$).

28. The invention as recited in claim 25, wherein the rotation combiner adjusts the locally generated reference to shift, in frequency, the demodulated signal substantially to baseband.

29. The invention as recited in claim 25, further comprising the steps of:

a signal quality measure processor configured to generate a signal quality measure (SQM) from the data-modulated signal; and

at least one other phase detector, each phase detector configured to generate a corresponding cost function error term based on a corresponding cost criterion, and wherein

the carrier tracking loop generates the angle with a cost function error term selected based on the SQM.

30. The invention as recited in claim 29, wherein the carrier tracking loop generates the angle based on the SQM by adaptively switching between either i) one of the cost error terms, or ii) a weighted combination of cost error terms that is combined with the approximation of the derivative.

31. The invention as recited in claim 29, wherein at least one other cost error terms is

a least mean square error term.

32. The invention as recited in claim 24, further comprising an equalizer having a forward filter and a feedback filter, the carrier tracking loop coupled to the forward filter to receive the demodulated signal.

33. The invention as recited in claim 32, wherein the estimate of the angle is based on the demodulated signal filtered with the forward filter.

34. The invention as recited in claim 32, further comprising a decision circuit to generate a decision for the data of the equalized, demodulated signal, and wherein the carrier tracking loop generates the estimate of the angle based on the decision for the data of the equalized, demodulated signal.

35. The invention as recited in claim 34, wherein the estimate of the angle is based on both the equalized, demodulated signal and on the decision for the data of the equalized, demodulated signal.

36. The invention as recited in claim 32, wherein the equalizer is either a linear equalizer or a decision feedback equalizer.

37. The invention as recited in claim 32, wherein the carrier tracking loop receives an SA- cost function error term to generate the estimate of the angle, the SA- cost function error term generated during a tap-coefficient update process of the equalizer.

38. The invention as recited in claim 32, wherein the equalizer employs the feedback filter operating on signals either in the passband or substantially near the baseband derived from the forward filter.

39. The invention as recited in claim 24, wherein the data-modulated signal is the carrier modulated by the data in accordance with a vestigial sideband (VSB) format.

40. The invention as recited in claim 24, wherein the data-modulated signal is a digital television signal having its data encoded in accordance with an ATSC standard.

41. A computer-readable medium having stored thereon a plurality of instructions, the plurality of instructions including instructions which, when executed by a processor, cause the

processor to implement a method for carrier phase detection in a demodulated signal formed from a data-modulated carrier, the method comprising the steps of:

a) generating an estimate of an angle between the carrier and the locally generated reference from the signal and based on a stochastic gradient of a single-axis cost function, the cost function being selected from a set of Bussgang-class cost functions; and

b) adjusting at least one of the frequency and phase of the demodulated signal based on the angle such that the magnitude of the angle is driven to a predetermined value.

42. A method of carrier phase detection in a demodulated signal formed from a data-modulated carrier, comprising the steps of:

a) generating, from the signal, an estimate of an angle between the carrier and a locally generated reference based on an estimate of a gradient of a single-axis cost function, the cost function being a Bussgang-class cost function; and

b) adjusting at least one of the frequency and phase of the demodulated signal based on the angle such that the magnitude of the angle is driven toward a predetermined value.